Title:

Ground Source Coil Drilling Platform – Annulus Drill

Final Report

Author:

Sam Diacon, Sheldon McCrackin, Josh Sorenson, Kyely Than

School of Mechanical and Aerospace Engineering, Oklahoma State University

Course:

MAE 4344 – Design Projects

ABSTRACT

Ground source heat pumps (GSHPs) use geothermal energy to heat and cool the operating fluid to pass through heat exchangers to condition the interior environment of commercial and residential structures. While GSHPs are usually more efficient than traditional heating/cooling systems, the up-front costs are high and the installation process can be very invasive to retrofit applications, which is a large part of the GSHP market.

The goal of this design project is to design a system capable of drilling a large annulus for installing a coil of HDPE pipe for heat transfer in a ground source heat pump system. Given dimensions of the annulus hole are 3 feet, 2.5 feet, 15 feet for outer diameter, inner diameter and depth, respectively.

The design of the machine performs two primary functions: annulus drilling and earth extraction. The purpose of drilling an annulus rather than a hole is to reduce the amount of dirt removed from the ground to lessen the installation costs and environmental effects, and to reduce the depth drilled into the ground from around 250 feet to 15 feet. This project is designed to reduce the overall environmental effects and cost of installing a ground source heat pump. The constraints include leaving the smallest possible footprint in a resident's yard, making the system easily operated by a trained individual, and reducing the cost of the operation and also the machine itself.

1. INTRODUCTION, BACKGROUND, AND PROBLEM STATEMENT

The goal of this design project is to design a system capable of drilling a large annulus hole for installing a coil of HDPE pipe for heat transfer in a ground source heat pump system. Given dimensions of the annulus hole are 3 feet, 2.5 feet, 15 feet for outer diameter, inner diameter and depth, respectively.

Ground source heat pumps (GSHPs) use geothermal energy to heat and cool the operating fluid to pass through heat exchangers to condition the interior environment of commercial and residential structures. While GSHPs are usually more efficient than traditional heating/cooling systems, the up-front costs are high and the installation process can be very invasive to retrofit applications, which is a large part of the GSHP market.

Current GSHPs are typically constructed in one of two ways. The most common method involves drilling vertical bore holes to insert HDPE pipe into the ground. The pipe travels to the bottom of the hole, makes a 180 degree turn via a U-bend, and travels upward to the surface. It is sometimes necessary to drill several holes to obtain the required length of pipe to achieve sufficient heating and cooling. It is common practice to use the same drilling techniques for water well drilling to bore vertical holes for ground source heat pumps. This method requires large trucks and machines to reach a depth of approximately 250 feet. Although this technique is effective, it is not practical. In residential areas, it is often hard to maneuver the large derrick truck into the desired drilling area. The large truck also destroys landscape and leaves a large footprint in the resident's yard while positioning itself for drilling. Traditional drilling techniques also require drilling mud which often leaks into the resident's yard along with drilling clippings. Even though long term savings may be experienced, these factors combined with the high cost of boring several wells can turn homeowners away from this form of ground source heat pumps.

The second common form of placing HDPE pipe into the ground for ground source heat pumps involves laying a looped pipe into a trench. In residential applications, this requires digging a deep trench throughout a resident's yard. These trenches can become very long to reach the required amount of pipe to obtain proper heat transfer. This often leads to the destruction of a resident's yard through trenching. Although cheaper, the landscape damage from this method often turns homeowners away from this method.

The design of the machine performs two primary functions: annulus drilling and earth extraction. The purpose of drilling an annulus rather than a hole is to reduce the amount of dirt removed from the ground to lessen the installation costs and environmental effects, and to reduce the depth drilled into the ground from around 250 feet to 15 feet. This project is designed to reduce the overall environmental effects and cost of installing a ground source heat pump. The constraints include leaving the smallest possible footprint in a resident's yard, making the system easily operated by a trained individual, and reducing the cost of the operation and also the machine itself.

DETAILED LIST OF PROJECT REQUIREMENTS / DELIVERABLES

At the end of the project, a base concept with a first order design approach is expected, which includes 3D models of all major mechanical components, their orientations, dimensions, and mechanical connections with the overall system. The environmental impact is minimized to make the annulus drill a viable alternative to conventional methods employed today. Total upfront system cost and the cost of ground source heat pump annulus drilling installation should be less than conventional methods as well. Sub-systems such as power sources, the drilling mechanism, dirt removal, frame and stabilization, and transportation method are defined. These deliverables, which can be found within the detailed description of work subsection, contain all necessary engineering analysis with clearly stated assumptions for the system.

PLAN OF ATTACK – SUMMARY

A plan of attack and timetable is constructed to complete this project and keep the progress of the team on schedule. The first phase consists of brainstorming possible methods of creating an annulus hole. All of the concepts are then collected and then the most viable option is chosen for further investigation. The second phase of the project includes identifying and researching the major subsystems required by the drilling system. Then, analytical engineering methods are applied to size all major subsystems and determine their characteristics. This includes all power sources and structural supports.

DETAILED DESCRIPTION OF FINAL DESIGN

The final design is shown in Figure 1. The design consists of a 20 foot derrick mounted onto a Freightliner M2106. The derrick is hinged on two legs and can be rotated about the hinges for transportation. This rotation is accomplished by 2 hydraulic rams. The derrick is lowered to 10 degrees with respect to the ground plane for transportation. This allows it to remain under the federal requirement for maximum height of 13.6 feet.

Housed inside of the derrick is the drill stem, PDC drill bit, vertical guide rails, annulus drive gears, core stabilizer, driving weights, and winch system. Four hydraulic motors power the entire system. The drill bit rotation, annulus revolution, winch system, and vacuum system each require a hydraulic motor.

The machine is capable of removing dirt in two ways. In the first method, the drill bit and stem travel around the annulus as they descend. This results in a spiral descending motion to create the annulus hole. The second method involves drilling a shallow hole, approximately 1-3 feet, and then rotating the stem 10 degrees and drilling another shallow hole. This is then continued until the annulus hole is complete. In both methods the drill stem itself does not spin. A motor or drive shaft is placed inside of the drill stem to spin the PDC bit only while the drill stem is stationary.

The drilling system's vertical motion is controlled by the winch system and the driving weights. The winch is guided by the vertical guide rails. The drilling system revolves around the annulus via two large rotating gears. The drill stem is connected to the primary gear with vertical bearings and the secondary gear is attached to the top of the drill stem.

The drilling machine does not use drilling fluids like traditional drilling methods. However, a dry vacuum is used for dirt removal. The vacuum hose and nozzle are connected to the drill stem. This allows the vacuum to follow the drill stem as the system drills and removes all dirt and clippings. The dirt is stored in a storage tank mounted on the truck bed.

A large hollow plastic cylinder which acts as a sheath is lowered around the annulus as the drilling process progresses. This stabilizes the annulus core and keeps it from collapsing. The plastic core is slotted vertically to allow the drill bit and stem to be retracted for the installation of the HDPE coils.

DETAILED DESCRIPTION OF WORK / KEY DECISIONS

Three major design ideas for creating the desired annulus hole were assembled. The first idea involves revolving a traditional drilling bit and string around the annulus while slowly plunging into the ground. This descending spiral motion creates the required annulus hole. This motion cuts approximately 3-6 inches vertically per revolution, and would require 30-60 revolutions per annulus hole.

The second drilling idea is similar to the first idea. However, instead of a constant spiral motion, the drill operates to a specified distance, approximately 1-3 feet, and then rotates the drilling mechanism and repeats. This process is repeated in a fixed degree rotation until the annulus hole is drilled. The general schematic can be seen in Figure 2.

The third idea involves plunging a vertical trencher into the ground in an octagonal pattern as shown in Figure 3. The octagonal pattern is made large enough to allow the circular coil of HDPE pipe to fit into the annulus hole. This method allows changes for the diameter of the hole for differently sized annuli. Compared to the two previous ideas, this method could possibly be more time-efficient. However, the system would experience great forces and moments, and would require more power than the previous two designs.

After the three drilling methods were determined, a decision matrix was created to determine the most viable option. As shown in Table 1, the trenching method could be eliminated due to its many negative factors including its estimated weight, power, and structural requirements. The spiral plunging method and the plunge and rotate method scored similarly in the decision matrix. Therefore, it was determined to go forward creating a prototype capable of drilling using both methods. In the future, this prototype needs to be tested to determine the better method of the two proposed methods. It is expected that the spiral plunging method would be better in soft soil formations, while the plunge and rotate method would be better suited for rocky soil.

Torque/Power for drill bit and stem

The design process began with the drilling process and mechanism. The forces required to drill through the earth must be determined to choose an appropriate power source and size the system. The torque and power required to spin the drill bit and stem in modern drilling are determined with complex computer models and previous drilling data. In *Drilling Engineering,* Azar states that less than 100 horsepower is typically required in vertical drilling. According to Azar, the horsepower can be reasonably estimated by an empirical approach. The horsepower is given as $HP = F * N$ where N is the drill stem RPM and F is the torque factor. The torque factor is estimated as F = 1.5 – 1.75 for holes < 10,000 feet. (1) Therefore, we used a torque factor of 1.5 as an absolute maximum requirement for our drilling system with the knowledge. This will most likely prove to be lower during prototype testing. Using the above empirical approach and N = 60 RPM, horsepower is estimated to be 90 HP. Back calculating for torque using the formula, $HP = \frac{2\, pi\, N\, T}{33000}$, gives the torque on bit to be 8,000 foot pounds.

The drill stem at full extension, 20 feet, is modeled as a cantilever beam, as seen in Figure 4, to calculate bending stress and forces. To retain a safety factor of 1.5, the maximum horizontal force is calculated to be 250 pounds. The drill stem's maximum stress, 23300 PSI, is located at the junction to the revolution driving mechanism. The maximum deflection, 8.8 inches, is located at the drill bit where the force is applied. These calculations are made using the following formulas and A36 steel properties:

$$\delta_B = \frac{F\, L^3}{3\, E\, I}$$

$$\sigma = \frac{M\, y}{I}$$

$E = 29{,}000{,}000\ PSI$
$\sigma_y = 36{,}000\ PSI$
$I = \frac{\pi\ (D_0^4 - D_i^4)}{64}$
$D_o = 3.5\ inch$
$D_i = 2.764\ inch$

Drill Stem Annulus Drive

Originally, the primary gearing system involved a set of planetary gears, shown in Figure 5. The smaller of the two gears is fixed to the drill string. The bigger gear remains stationary while the smaller gear is driven by a motor causing it to rotate around the bigger gear's inner circumference. However, this led to a hydraulic line interference as the drill stem and connected hydraulic motor spun around the annulus. The general gearing system was improved to prevent hydraulic line interference. The new primary gearing system, Figure 6, still involves two gears. The drill string is fixed to the big gear. The smaller gear, which is not shown in the figure, is attached to the outer teeth of the bigger gear and is driven by a motor to allow rotation along the outer circumference of the bigger gear. The drill string is fixed to the bigger gear while the bigger gear moves radially for the drill bit to change angular position. In this configuration the motor is stationary, instead of rotating around the annulus. The top of the drill string is fixed to the secondary gear to provide guidance and prevent the drill string from walking.

The force required to revolve the drill stem around the annulus hole is calculated to be 172 pounds. This is calculated using the drill stem horizontal force, 250 pounds, and the geometry involved in the annulus drive mechanism, seen in Figure 7. The 172 pound force is calculated using the formula $F_o = \frac{F_i\, r_i}{r_o}$ with $r_i = 16.5$ inches and $r_o = 24$ inches. Assuming the motor has a 6 inch drive gear, the hydraulic motor requires 43 foot pounds of torque to revolve the drive mechanism.

Winch Power

The total power required to drive the winch controlling the vertical motion of the drill stem, driving blocks, and retaining cylinder is calculated to be 31 HP. The total weight of the moving system is determined to be 2000 pounds, see Table 2. The winch is sized to be able to safely raise and lower 8000 pounds for a factor of safety of 4. The ability to withdraw 4 times the weight of the moving drilling system is also used in the event that the drill stem becomes stuck in the ground during retraction. From the winch systems free body diagram, Figure 8, it is determined that a 4 inch diameter drum would require 2667 ft lbs of torque. The power required is 31 HP, calculated from $HP = \frac{2\,\pi\, N\, T}{33000}$ at a maximum speed of 60 RPM or 2 feet per second.

Hydraulic Cylinder Dimensions and Power

The drilling machine possesses two 4 inch hydraulic cylinders to raise and lower the 4000 pound derrick for transportation. These hydraulic cylinders are mounted to both the truck bed and derrick truss with pinned connections. This allows the rotation at the connections as the truss moves radially around its pinned connection to the truck bed. The hydraulic rod is attached at a vertical height of 5 feet on the truss to connect at the truss's horizontal support members. The truss is lowered to an angle of 10 degrees for transportation and then raised to vertical for all drilling operations. 10 degrees was chosen to allow the total height of the drill rig to be 11.7 feet tall while being transported, which is approximately 2 feet less than the federal requirement of a maximum travel height of 13.6 feet. 10 degrees was determined by taking the height of the truck bed, 40 inches, and the geometry associated with the derrick's radial movement, Figure 9. The hydraulic system is placed 5.8 feet away from the base of the derrick to allow the cylinder/truss connect to be perpendicular during transportation at 10 degrees. The hydraulic rod itself travels 4.75 feet during the process of raising the derrick.

The force on the hydraulic cylinders is calculated by summing the moments about the pivot point in the free body diagram of the system, Figure 10. The force required is calculated to be 7880 lbs. Two hydraulic cylinders which are both capable of lifting this weight were chosen for safety. Therefore, each cylinder is rated at a minimum of 8000 lbs. The pressure required to drive these 4 inch cylinders, 637 PSI, can be calculated by the formula, $P = \frac{F}{\frac{\pi d^2}{4}}$.

Annulus Stabilization

With the given parameters of 3 ft and 2.5 ft for the outer and inner diameter, respectively, the core of the annulus would be unstable at a depth of 15 ft. To stabilize the core, a sheath is lowered into place around the core as the hole was being drilled. The sheath is left in place following completion of the hole and then be removed after the helical HPDE U-pipe had been set in place in the hole. To keep weight and cost down, the sheath is made out of PVC.

Vacuum system calculations

To properly size the vacuum system for the dirt extraction, the pressure requirement for the dirt to travel upward is calculated using the standard pipe flow pressure drop equation which is derived from the Darcy-Weisbach equation and can be seen by the following equation.

$$\Delta p = f \frac{L}{D} \frac{\rho V^2}{2}$$

With a total dirt volume of 32.4 ft^3 or 242.3 gallon, the dirt handling flow rate is assumed to be 300.0 CFM. The pipe connected to the vacuum is flexible rubber tubing with wire reinforcement which has a pipe roughness of 0.3mm. The pipe diameter and length is 3 inches and 30 feet, respectively. The mixture going through the pipe is dirt and air, with an effective density of 76.16 lb/ft^3 and 0.073 lb/ft^3, respectively. Assuming homogenous flow, the density of air is used. The kinematic viscosity of air is also used, which is 1.69E-04 ft^2/s, to calculate Reynolds number. Reynolds number and friction factor is determined to be 1.51E+05 and 2.92E-02, respectively. With a calculated velocity of 101.7 ft/s, the pipe flow pressure drop is 2.86E-01 psi. A PV-250 vacuum excavator from Pacific-Tek is chosen for the dirt extraction. The vacuum system has a 25 Hp gas engine and 525 CFM blower. The vacuum is chosen because the system excavates debris from dry dirt to wet mud, and it is attached to a 250 gallon container, which meets the requirement of 243 gallons. The current PV-250 vacuum system is overpowered but a more suitable option with less power will be determined in the future.

Finite Element Analysis (FEA) on Derrick

The derrick model and its components can be seen in Figure 11, Figure 12, and Figure 13. Finite element analysis is performed on the truss structure to determine critical stress points of the derrick during normal operation. The derrick is placed under two main loading configurations during setup and operation. The first loading scenario is an evenly distributed vertical load due to the moving block, core cylinder, drill stem, drill bit, and the tracks attached to the derrick. Figure 4 shows a representation of the loading, with the bottom struts of the derrick in fixed position and a 3000 lb load evenly distributed along the top beams of the structure. This figure includes the necessary weight on bit estimate due to the 500lb per 1 inch of diameter rule, along with the weights of all previously mentioned components. The current derrick is made of 2x2 inch square tubing with a ½ inch wall thickness, and the corners are filleted at ½ inch. The four square beams at the top of the derrick are made of 2.5 x 2.5 inch square tubing with a ½ inch wall thickness as the highest loads and deflections are seen in these beams. The diagonal piping along the truss structure is 1 inch sch. 40 pipe with an inner diameter of 1.05 inches, an outer diameter of 1.32 inches, and a nominal thickness of 0.13 inch. The resulting stresses are shown in Figure 5. The maximum observed stresses are found in the top four corners of the derrick, with the highest stress of 3.35E+07 N/m^2. The yield stress of the chosen A36 steel is 2.50 E+08 N/m^2 which gives the smallest safety factor of 7.47.

The second loading scenario is the hydraulic force applied to the derrick to raise and lower the structure. A normal force was applied to the two joints located at 5 feet from the bottom of the derrick. Figure 6 shows the loading applied to the derrick. Two hydraulic pistons each produce a force of 3825 lbs to evenly distribute the load across the derrick. The resulting stresses are shown in Figure 17. The maximum observed stresses are found in the beams located on the same plane as the applied force, with the highest observed stress of 1.60E+07 N/m^2. The yield stress of the chosen A36 steel is 2.50 E+08 N/m^2 which gives the smallest safety factor of 15.6.

Truss Analysis

The derrick structure was analyzed in 2-D from the side to determine the maximum amount of forces that each member would be under while the raising and lowering operations. Two critical positions were identified to calculate: horizontal (0°) and the break over point (45°). The horizontal position is the most critical because it requires a higher amount of pressure while traveling a greater distance to stand upward. To meet the bridge height requirements for the structure, the maximum traveling angle is calculated to be 10°. Even though having the derrick laying flat on the truck bed requires more power, it is more preferable to have the system laying down for ease of transportation and safety. **Error! Reference source not found.**8 and **Error! Reference source not found.**9 show the calculations performed. Highest force comes from member directly connected in line with hydraulic rams at 1125 lbs.

Transportation

For the final system, a truck is used for transportation, using the truck bed for the foundation of the structure and PTO as the power supply source. The PTO gear is mated to the transmission to allow power routing to a central hydraulic pump. Freightliner's M2106 is currently the prime candidate for the platform. The truck is customizable and can be a range of frame lengths with additional engine options that will suit the design parameters.

Key Conclusions and Decisions

Hydraulic motors are utilized to power the entire system. A central hydraulic system allows for a main large pump located away from the major components to supply power to smaller hydraulic motors as needed. This factor makes hydraulic motors superior to electric and mechanical motors because power can be easily transported through hydraulic lines.

For the drilling process, no drilling fluids are used. Dry drilling creates less environmental effects and requires smaller storage tank for the dirt. Since density of air is much less compared to water or drilling fluid, the power required to extract the dirt is less for dry drilling. This method also eliminates the need for fluid handling and dirt separation, along with reducing the environment effects of using a drilling fluid.

A cylindrical column is implemented into the design to provide core stabilization. Adding the column not only helps to provides a guide to the drill bit but also prevents the core from collapsing while the drill bit creates the annulus.

The placement of the gear system is crucial in the design. Placing the primary gear at the base of the drilling apparatus minimizes the moment the drill string would experience while drilling and provides more control on the drill bit. The secondary gear at the top of the drill string provides an attachment point for the winch system and driving blocks, along with maintaining stability and control of the upper drill stem.

A Freightliner M2106 truck is chosen as the foundation of the entire drilling system. Even though minimal environment impact is originally desired, the size of the system, including the derrick and the cylindrical column, requires the usage of a truck-based structure. A benefit of an industrial style truck is using power take-off (PTO) from the truck engine to power the hydraulic pump which powers the hydraulic motors used for drilling, winch operations, and derrick raising and lowering. Compared to purchasing a separate power source, using power from the truck engine saves cost and weight on the entire system.

Hydraulic cylinders are attached 5 feet from the bottom of the derrick structure and are used to raise and lower the structure. With a 20ft derrick structure, the derrick structure has to be lowered during transportation to meet federal height regulations for issues such as bridge clearance. With the fact that disassembling the derrick requires extra labor and time, lowering the derrick structure for transportation is a feasible option. Thus, the derrick structure can be either lowered down flat on the truck bed or resting on top of the truck cabin depending on the length of the truck bed.

EVALUATION OF FINAL DESIGN

From the onset, it was predicted that the annulus core would not be able to stand alone. A cylindrical column is implemented into the design to provide core stabilization. Adding the column not only provides a guide to the drill bit but also prevents the core from collapsing while the drill bit creates the annulus.

All major sub-systems are defined, which includes the power source, drilling mechanism, dirt vacuum, frame and stabilization, and transportation. SolidWorks design are created for all of the listed major sub-systems.

Currently, the weight of the derrick structure is very large and can be altered to reduce the weight. The derrick provide support for the weight of the drill stem, drill bit, moving block, core cylinder, and tracks. With the total load of the previously mentioned components, the derrick design has a safety factor of 7.47. With that high of a safety factor, the derrick design has potential for weight reduction.

Compared to water well rigs in the current market, the current design is similar in power requirement, structural components and cost. However, the goal of the project is to design a smaller system compared to large derrick truck to allow easy maneuverability into resident's backyard without property damage.

RECOMMENDATIONS FOR FUTURE WORK

Future work includes minimizing the weight of the derrick structure. The structure is currently overdesigned and improvements can be made by removing a few supports in the structure or using smaller pipes.

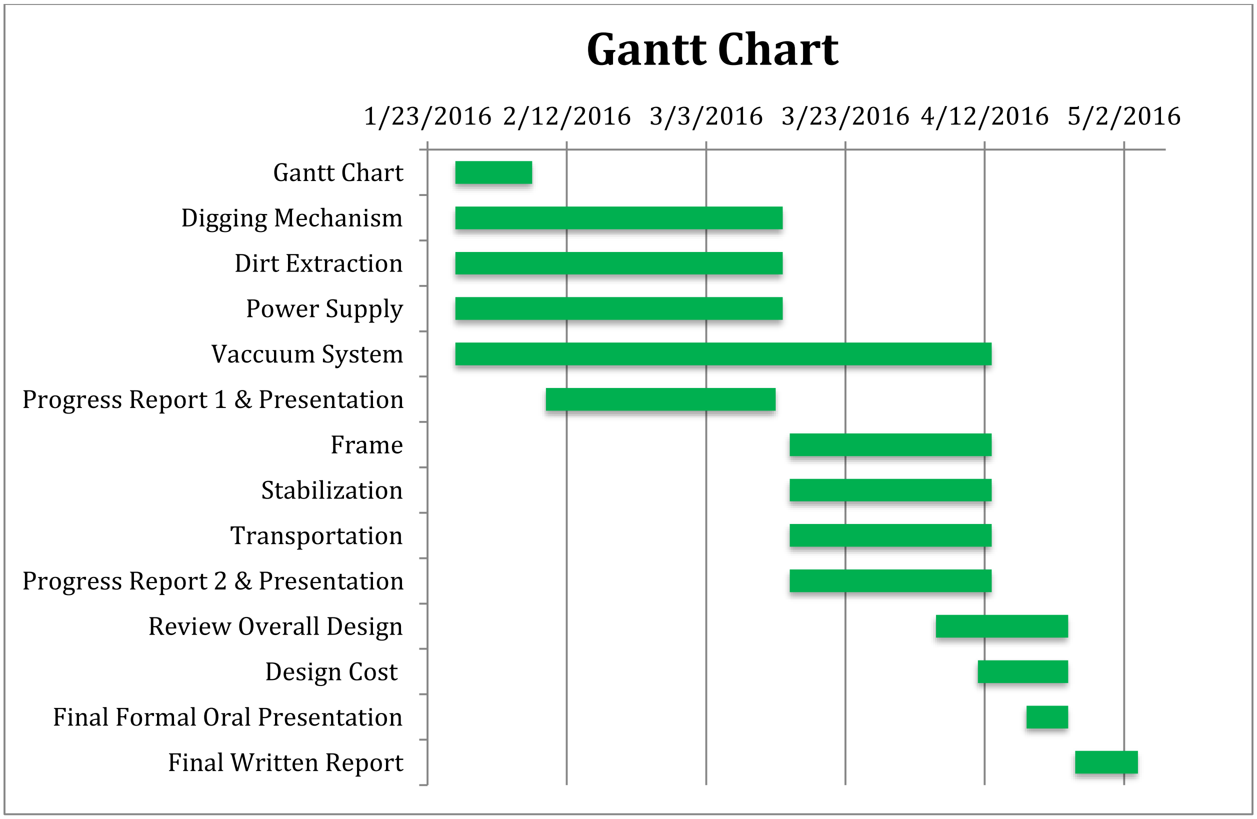
The structure of the truck bed also needs to be determined by a future group to make sure the loads applied during drilling do not cause the truck bed or chassis to fail.

The current vacuum system is chosen because of its capacity of 250 gallons, which meets the requirement of 243 gallons for dirt storage, and its versatility of dry dirt and wet mud vacuuming. Since the working fluid is air, wet mud vacuuming capabilities are not necessary and a different vacuum system can be chosen with a lower power usage and cost.

As the project develops, a future group will build a scale working model of the drilling rig for testing.

REVISED GANTT CHART

The final Gantt Chart can be seen in the figure below. It is important to note that all tasks for the first order design are completed.



REVISED BUDGET TABLE

The team required no budget during the first order design of this system. However, a cost table shown below gives an estimate of material costs expected with prices of actual usable components listed. The sources for the prices can be found in the appendix. The total cost does not include labor.

Estimated Cost			
Item	**Price/Unit**	**No. Units**	**Total Price**
Drill Stem (ft)	$36.51	20	$730.20
Drill Bit	$140.80	1	$140.80
Derrick Tubing (ft)	$5.14	250	$1,285.00
Support Cylinder	$643.99	1	$643.99
Gearing System	$2,000.00	2	$4,000.00
Derrick Guides and Drive Weight	$1,500.00	1	$1,500.00
Hydraulic motor	$179.99	4	$719.96
Pto Pump	$599.29	1	$599.29
Hydraulic Hose	$13.00	100	$1,300.00
Vaccum System	$161.58	1	$161.58
Dirt Container	$56.64	6	$339.84
Freightliner M2106	$86,000.00	1	$86,000.00
		Total	$97,420.66

8. FIGURES

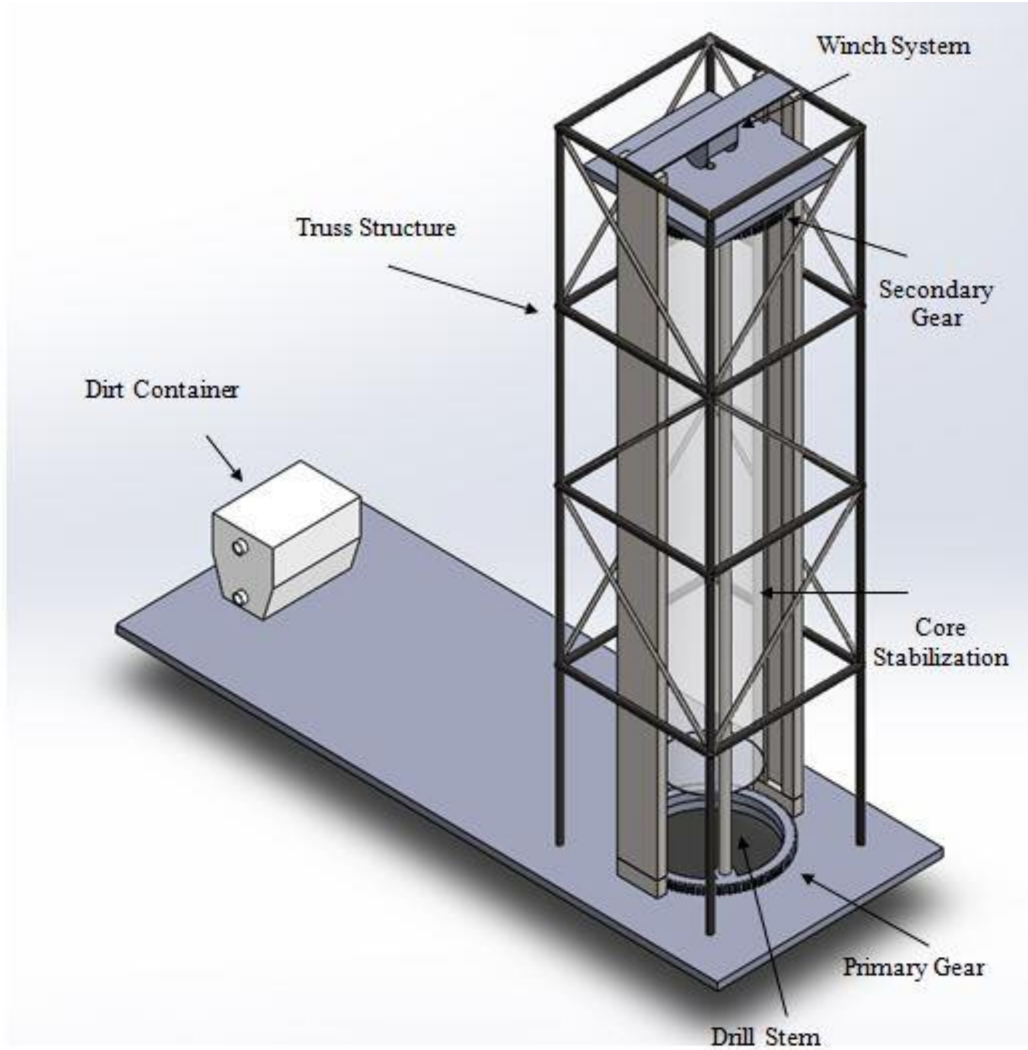


Figure 1 System Schematic

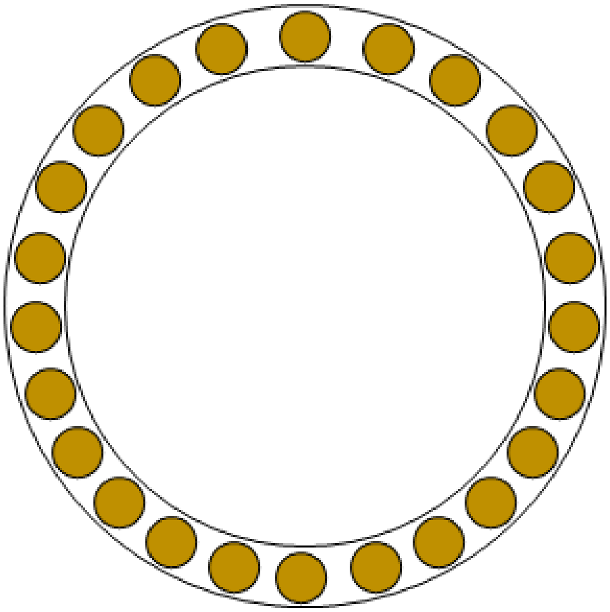


Figure 2 Plunge and Rotate

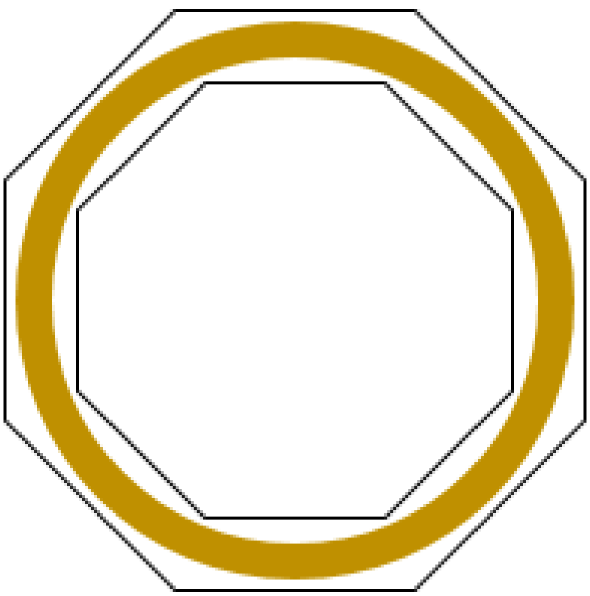


Figure 3 Trencher Method

Table 1 Decison Matrix

	Spiral Drill	Trencher	Plunge-and-Rotate
Weight	1	-1	1
Maximum Moment	0	-1	1
Easily Accessible Components	0	1	0
Power Required	0	-1	1
Structure	1	-1	1
Transportability	1	0	1
Cost	-1	0	-1
Capacity for dirt removal	0	0	0
Total	2	-3	4

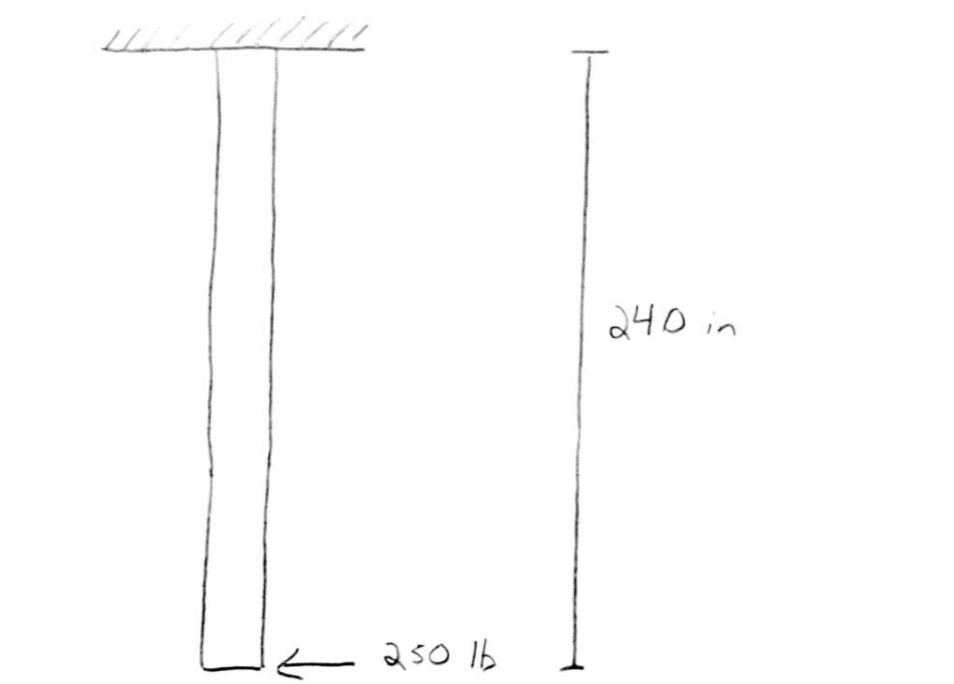


Figure 4 Drill Stem FBD

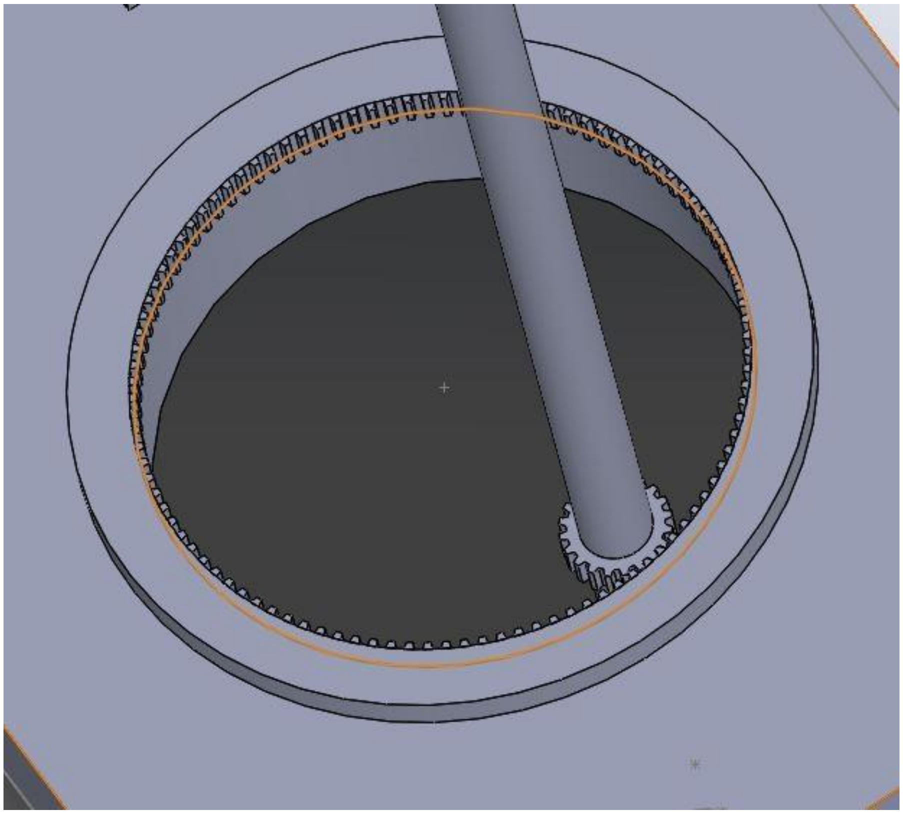


Figure 5 Planetary Gearing System

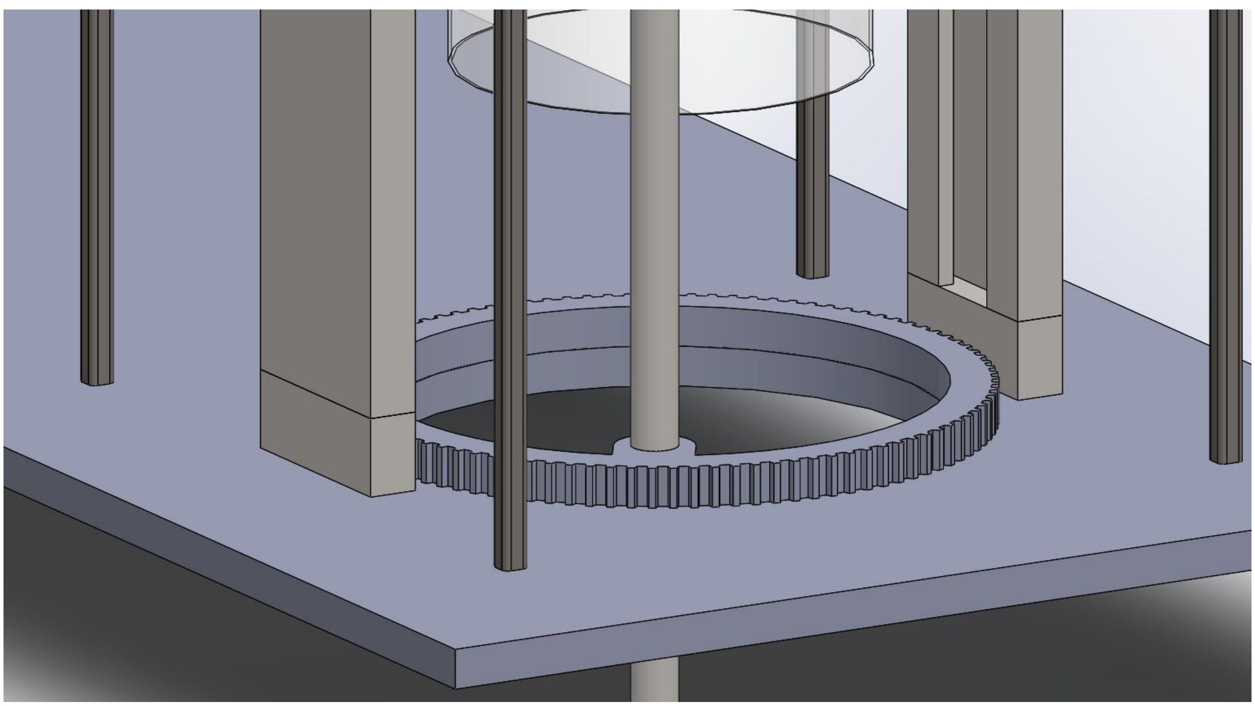


Figure 6 Primary Gear

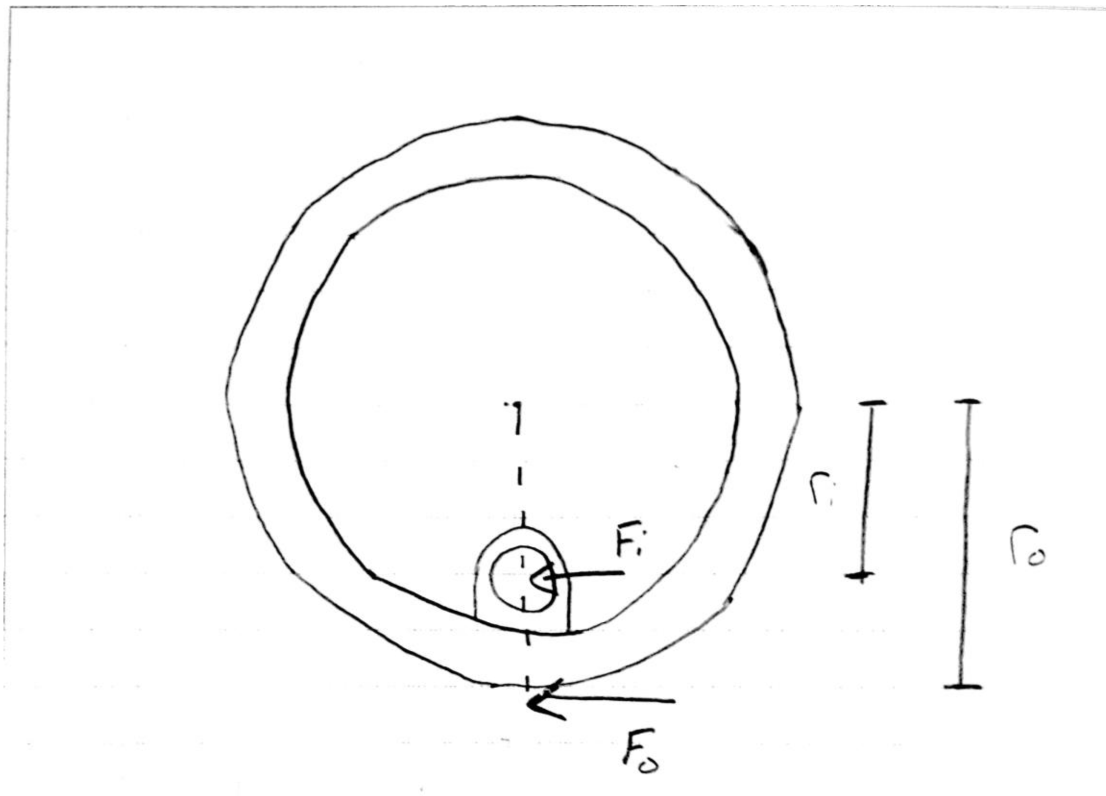


Figure 7 Primary Gear FBD

Table 2 Weight Estimates

Component	**Weight (lbs)**	**Moved by Winch**
Moving Block	1200	Y
Track System	500	N
Winch	200	N
Primary Gear	300	N
Secondary Gear	300	Y
Drill Bit	15	Y
Derrick	988	N
Drill Stem	245	Y
Plastic Cylinder	182	Y
Total Derrick Weight	**3930**	
Total Winch Weight	**1942**	

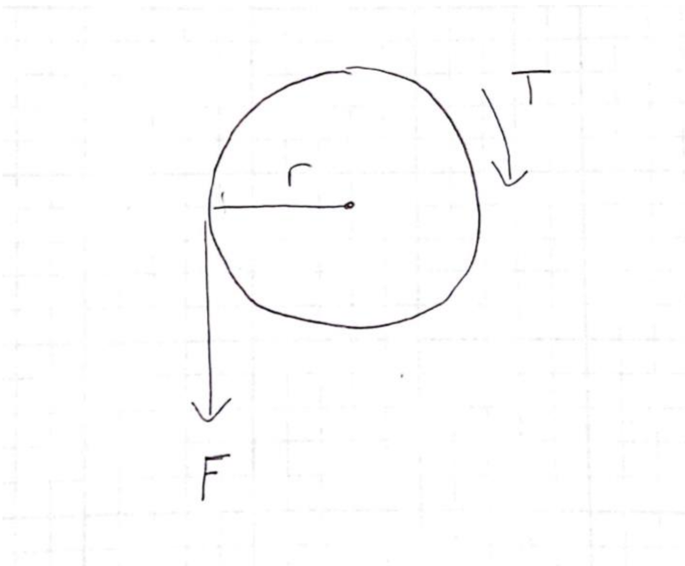


Figure 8 Winch FBD

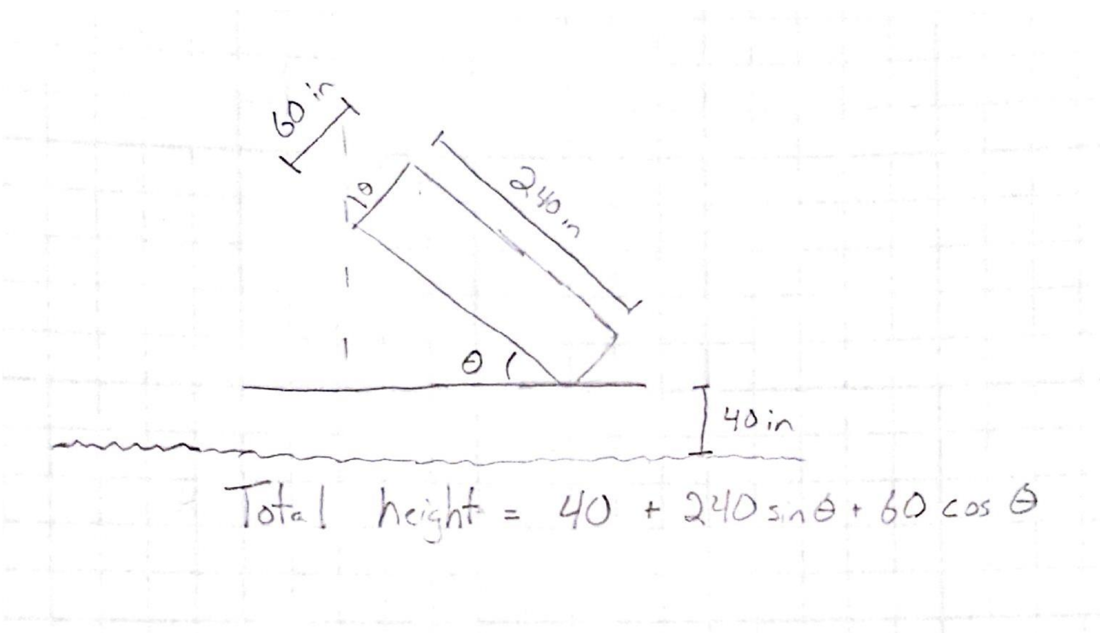


Figure 9 Height Geometry FBD

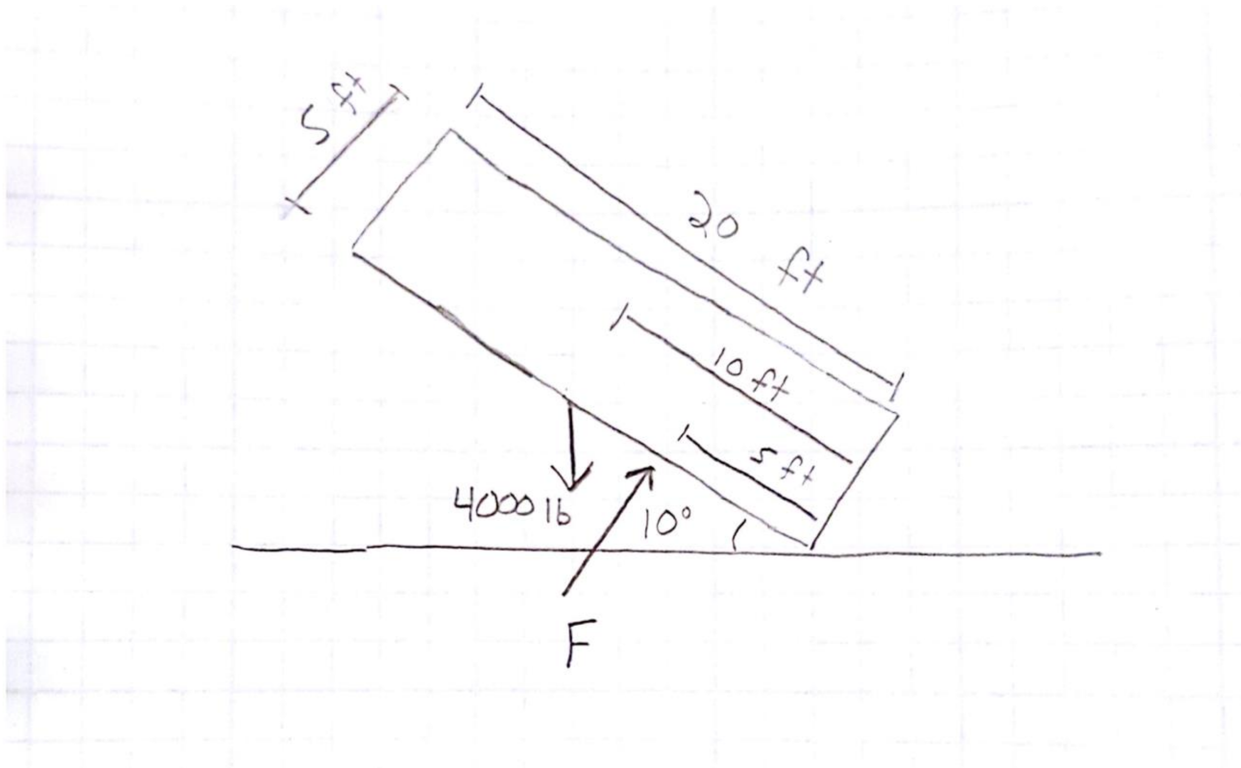


Figure 10 Truss Hydraulics FBD

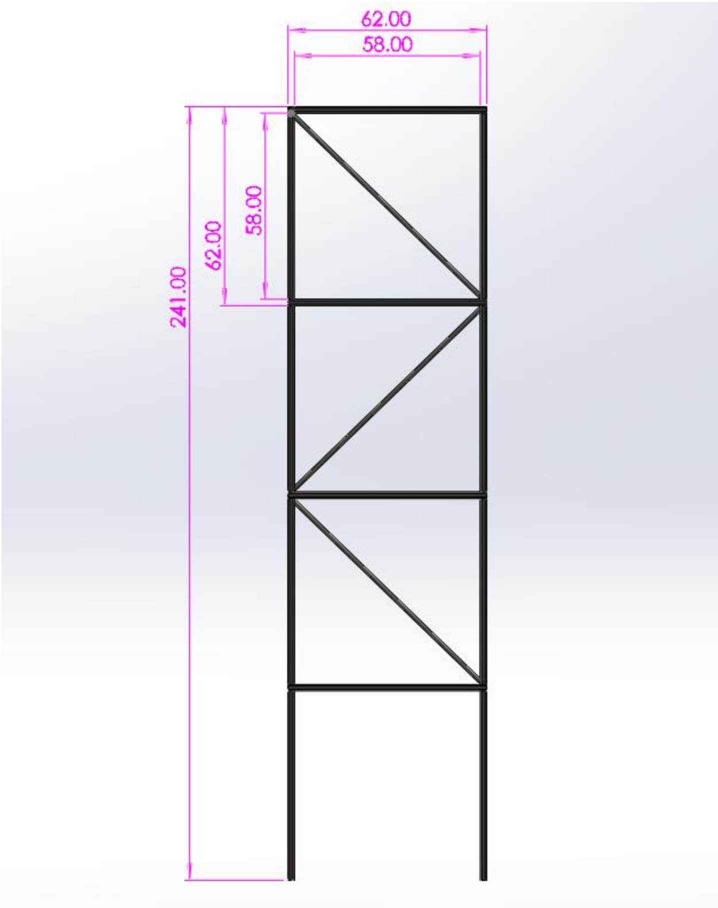


Figure 11 Side-view of derrick, all dimensions in inches

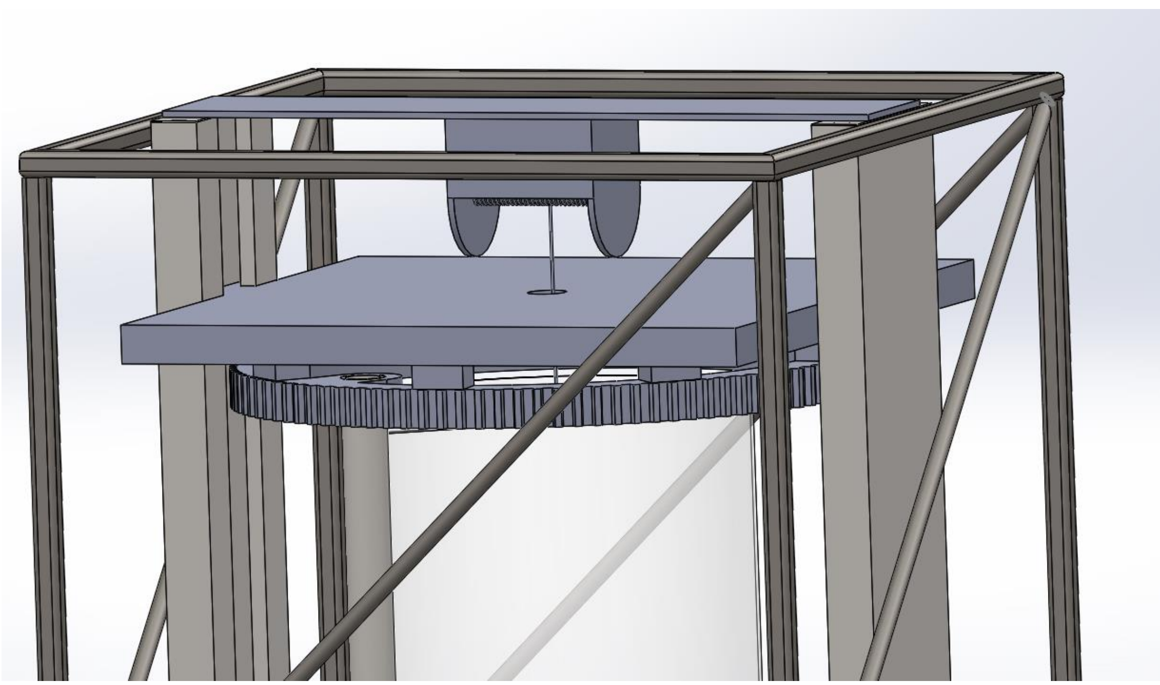


Figure 12 View of winch, supports, gearing, and plastic cylinder

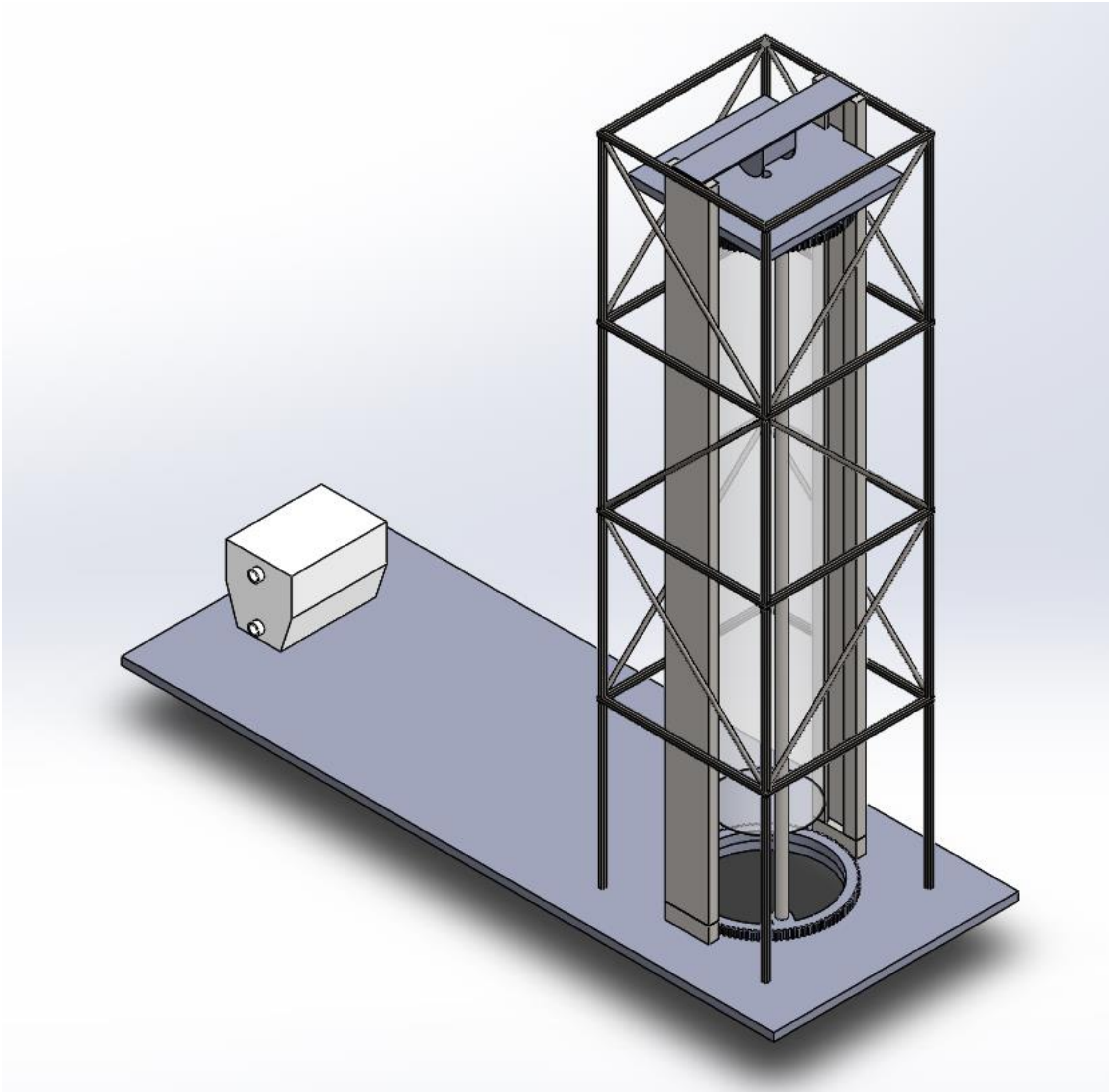


Figure 13 Isometric drawing of drilling rig

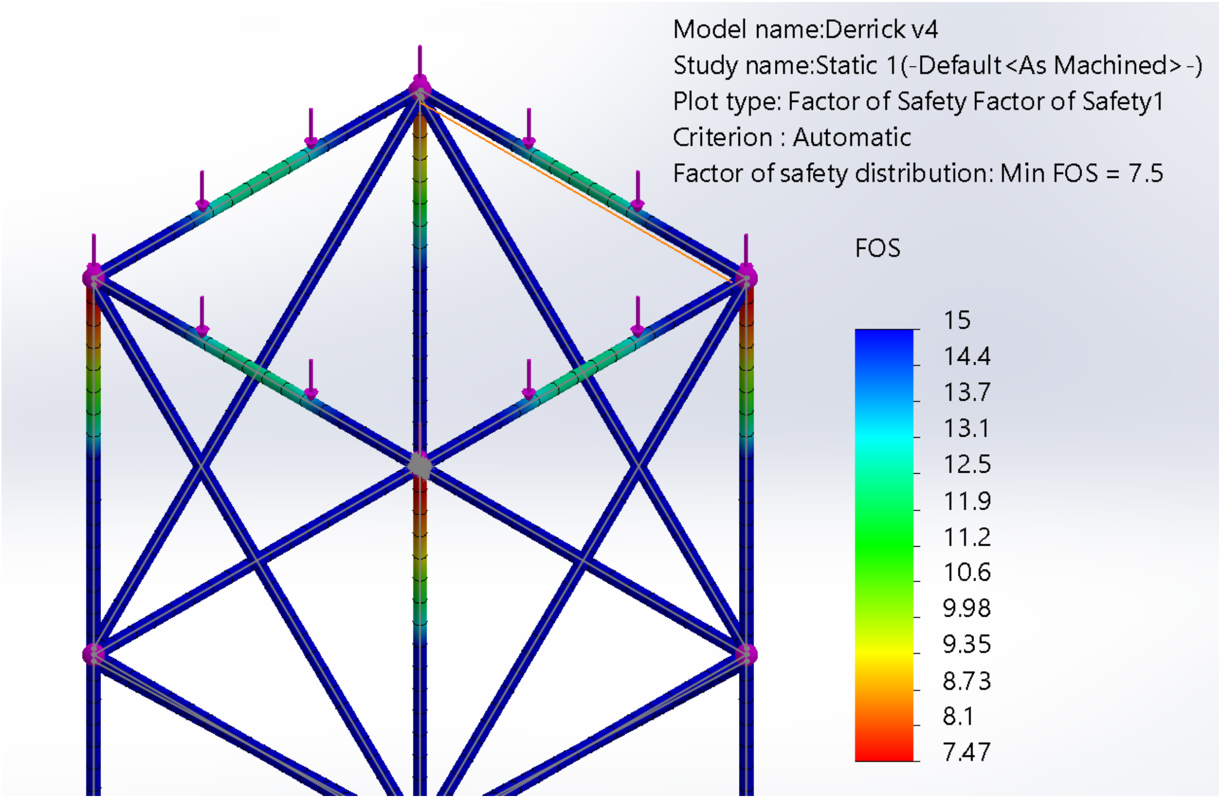


Figure 14 Factors of safety for loading configuration 1

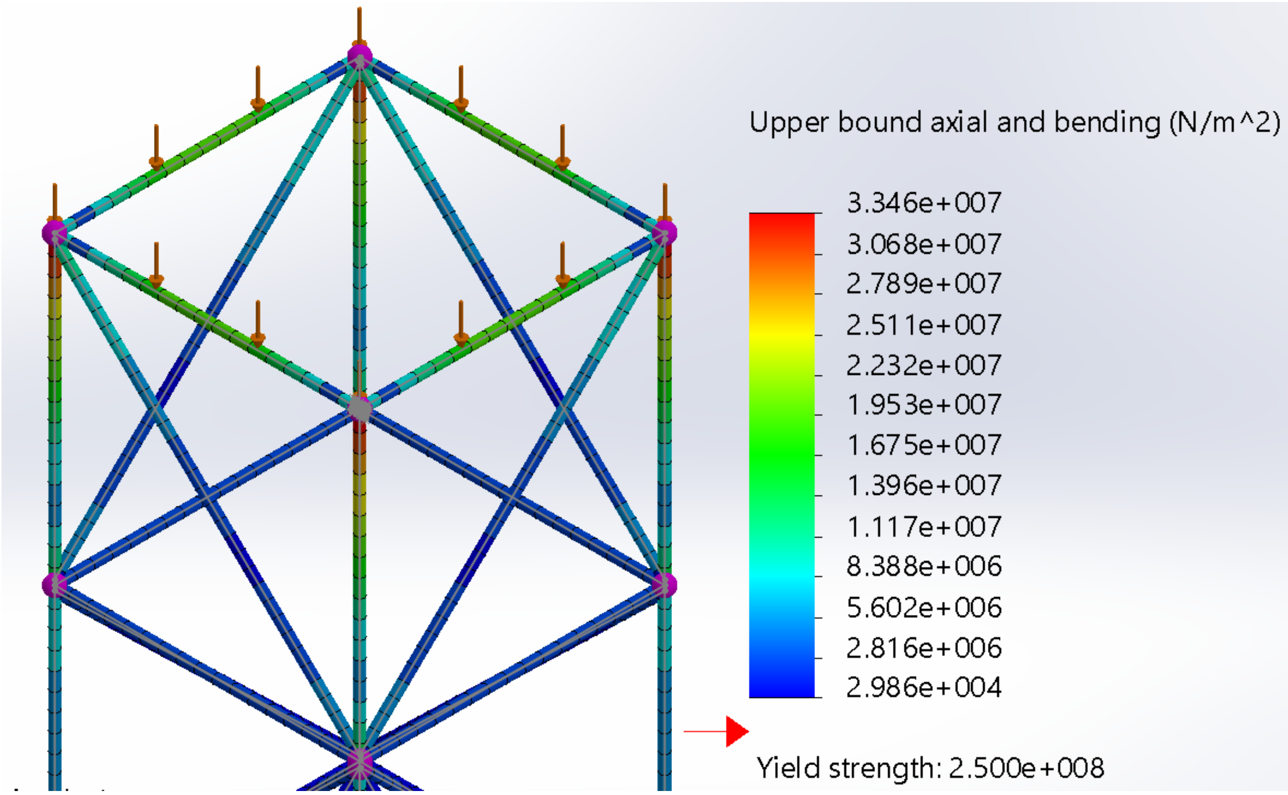


Figure 15 Stresses on loading configuration 1

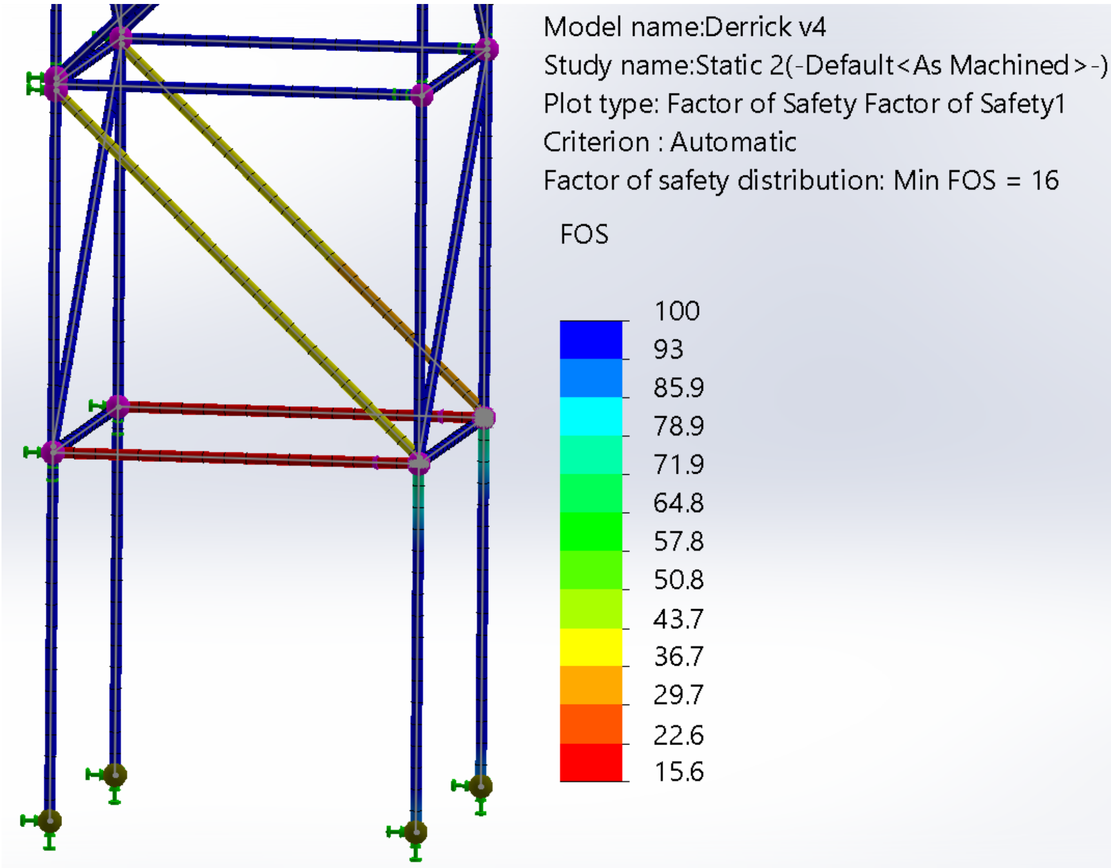


Figure 16 Factors of safety on loading configuration 2

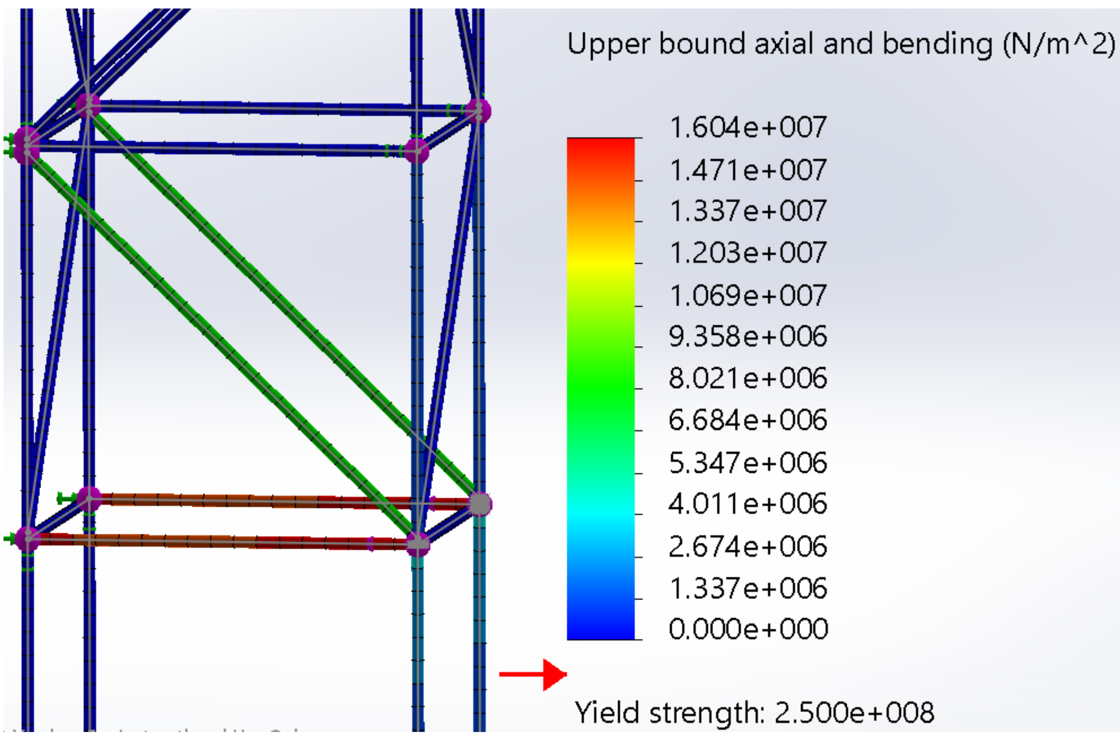


Figure 17 Stresses on loading configuration 2

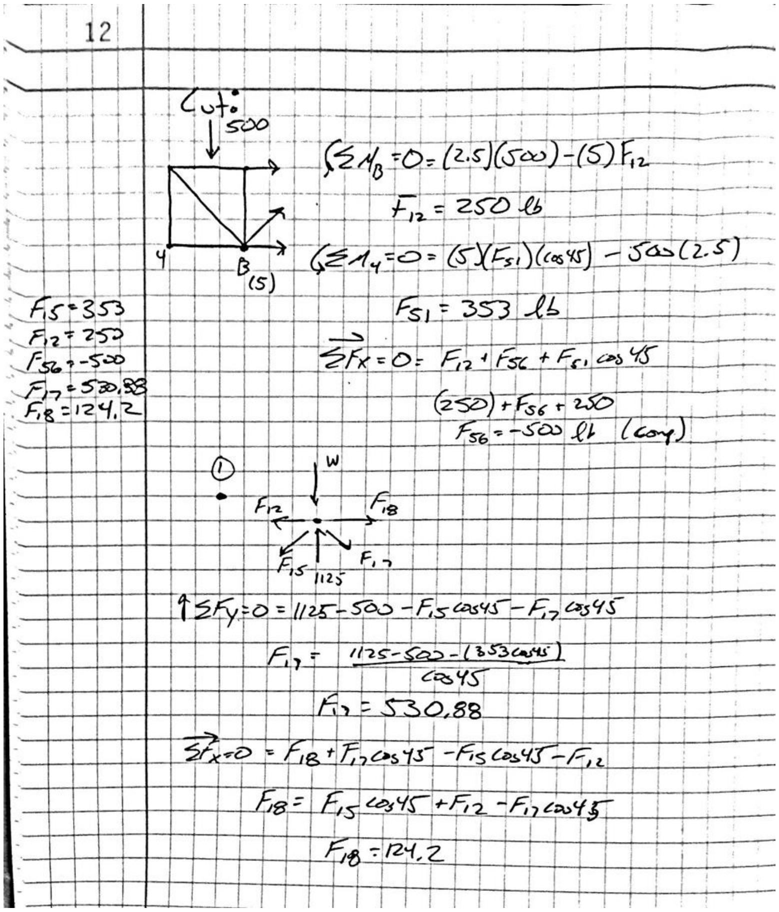


Figure 18 2D Truss Analysis

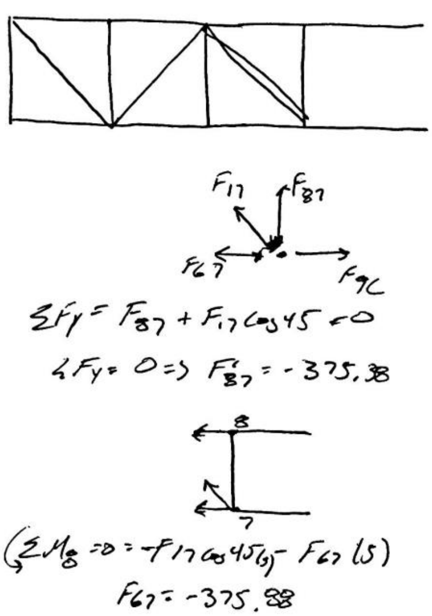


Figure 119 2D Truss Analysis Continued

9. REFERENCES

(1) Azar, Jamal J., and G. Robello. Samuel. Drilling Engineering. Tulsa, OK: PennWell, 2007. Print.

10. APPENDIX

Estimated Cost				
Item	**Price/Unit**	**No. Units**	**Total Price**	**Source**
Drill Stem (ft)	$36.51	20	$730.20	https://onlinemetalsupply.com/316-stainless-steel-pipe-3-inch-x-12-sch-10s-3-5-od-x-3-26-id-seamless/
Drill Bit	$140.80	1	$140.80	http://www.ebay.com/itm/like/130590461900?lpid=82&chn=ps&ul_noapp=true
Derrick Tubing (ft)	$5.14	200	$1,028.00	http://www.metalsdepot.com/products/hrsteel2.phtml?page=sqtube
Support Cylinder	$643.99	1	$643.99	http://www.agrisupply.com/prolink-ultra-bell-spigot-storm-water-pipe/p/36684/
Gearing System	$2,500.00	2	$5,000.00	Estimated
Derrick Guides and Drive Weight	$2,000.00	1	$2,000.00	Estimated
Hydraulic motor	$179.99	3	$539.97	pla&utm_source=Google_PLA&utm_medium=Hydraulics%20%3E%20Hydraulic%20Motors%20%2B%20Mo
Pto Pump	$599.29	1	$599.29	dware_pumps_utility_pumps_a1_other:na:na:na:na:na:2&code=PLA15&ds_c=gen_hardware_a1&ds_cid&
Hydraulic Hose	$13.00	20	$260.00	7aVEuZHYg5UDyYrcxrUECAkQASDezc8eKBRgyabxi8ikrBSgAbeWptQDyAEHqgQnT9Cn-
Vaccum System	$161.58	1	$161.58	07164-
Dirt Container	$56.64	6	$339.84	http://www.metalsdepot.com/products/stainless2.phtml?page=sheet&LimAcc=%20&aident=
Total Cost			**$11,443.67**	